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Plant Hormones in War and Peace

Science, Industry, and Government in the Development of Herbicides in 1940s America

*By Nicolas Rasmussen**

ABSTRACT

This essay describes the emergence of "hormone" herbicides from academic plant physiology research in America in the late 1930s and 1940s, attending especially to the role of interactions between university scientists, industrial concerns, and government (particularly agricultural) agencies. The importance of an intellectual shift among the physiologists to viewing hormones as plant toxins rather than growth stimulators, spurred by wartime events, is discussed. The essay concludes by exploring the postwar marketing of these hormones as agrichemicals and as lawn treatments for suburban consumers, placing these in the economic and ecological context of other contemporary developments in farming technique.

IT IS A RECURRING THEME AMONG HISTORIANS OF SCIENCE that World War II dramatically altered science, particularly in the United States. Scientists of every stripe joined in the war effort, and whether or not their fields were selected by the government for special attention, most did what they could to ensure victory. In many of the physical sciences, large military projects such as the development of the atom bomb and radar are viewed as having suddenly brought a new order of magnitude to research, in terms of budgets and numbers of personnel. And, thanks to the greater availability of military funding for physics in the cold war era, together with new sources of government support for basic research such as the Office of Naval Research and the National Science Foundation, postwar science in many physical fields continued on the new, larger scale without abatement. In the biomedical sciences, too, it is widely agreed that an era of Big Science was ushered in during World War II: large-scale government war projects involving bi-

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ologists (such as penicillin production, blood fractionation, and antimalarial drug testing) were followed by greatly increased levels of National Institutes of Health funding in the postwar period.[1]

The connection between war and the advancement of science and technology is particularly remarkable for agriculture, in that a striking number of changes on the farm during the twentieth century have mirrored changes on the modern battlefield. Tractors and tanks developed side by side. Synthetic nitrogen fertilizers were manufactured cheaply in ammonia plants built mainly to make nitrate explosives. Modern organic insecticides emerged from gas weapon research between the wars, while aerial spraying owes much to air combat methods and technology initially developed during World War I. World War II saw the introduction of DDT through a government project on disease control aimed at louse and mosquito extermination, and after the war economic entomology was quickly transformed by such new insecticides into a largely chemical discipline. The first powerful selective herbicides, chemicals used to kill weeds in the place of old labor-intensive cultivation methods, similarly emerged from a World War II military research project that enlisted biologists. In this essay I relate the story of the introduction of modern herbicides during the war—a story more complex than previous scholarship has suggested—and at the same time address some of these persistent questions about the impact of the war on the life sciences and on agricultural science and technology in particular.[2]

The story of the development of agricultural herbicides is complex in that they were discovered not only by biologists pursuing secret military research during World War II but also independently by at least three other research groups at roughly the same time. It appears, I will argue, that the herbicides might have been discovered earlier if not for a conceptual obstacle, namely, that the sorts of chemicals in question were thought of as growth-promoting hormones rather than as plant killers by the scientists involved in study-

[1] On World War II and the changes it brought to physical sciences see the contributions in Paul Forman and Jose M. Sanchez-Ron, eds., *National Military Establishments and the Advancement of Science and Technology* (Dordrecht: Kluwer, 1996), and in Peter Galison and Bruce Hevly, eds., *Big Science: The Growth of Large-Scale Research* (Stanford, Calif.: Stanford Univ. Press, 1992). See also Forman, "Behind Quantum Electronics: National Security as Basis for Physical Research in the United States, 1940–1960," *Historical Studies in the Physical and Biological Sciences,* 1987, *18*:149–229; and Nathan Reingold, "Science and Government in the United States since 1945," *History of Science,* 1994, *32:*361–386. On life sciences during and immediately after World War II see Angela Creager, "Biotechnology and Blood: Edwin Cohn's Plasma Fractionation Project, 1940–1953," in *Private Science,* ed. Arnold Thackray (Philadelphia: Univ. Pennsylvania Press, 1998), pp. 39–62; Jean-Paul Gaudillière, "The Molecularization of Cancer Etiology in the Postwar United States: Instruments, Politics, and Management," in *Molecularizing Biology and Medicine: New Practices and Alliances, 1910s–1970s,* ed. Soraya de Chadarevian and Harmke Kamminga (Amsterdam: Harwood, 1998), pp. 139–170; Peter Neushul, "Science, Government, and the Mass Production of Penicillin," *Journal of the History of Medicine and Allied Sciences,* 1993, *48:*371–395; John Perkins, "Reshaping Technology in Wartime: The Effect of Military Goals on Entomological Research and Insect-Control Practices," *Technology and Culture,* 1978, *19:*169–186; Nicolas Rasmussen, "The Midcentury Biophysics Bubble: Hiroshima and the Biological Revolution in America, Revisited," *Hist. Sci.,* 1997, *35:*245–293; and Stuart Strickland, *Politics, Science, and Dread Disease: A Short History of United States Medical Research Policy* (Cambridge, Mass.: Harvard Univ. Press, 1972). For a somewhat different view of the impact of the war on life sciences see Rasmussen, "Of 'Small Men,' Big Science, and Bigger Business: The Second World War and Biomedical Research in America" (under review).

[2] Edmund Russell III, "'Speaking of Annihilation': Mobilization for War against Human and Insect Enemies, 1914–1945," *Journal of American History,* 1996, *83:*1505–1529; Lewis Nelson, *History of the U.S. Fertilizer Industry* (Muscle Shoals, Ala.: Tennessee Valley Authority, 1990); Reynold Wik, "The American Farm Tractor as Father of the Military Tank," *Agricultural History,* 1980, *54:*126–133; Paolo Palladino, *Entomology, Ecology, and Agriculture* (Amsterdam: Harwood, 1996); John Perkins, *Insects, Experts, and the Insecticide Crisis* (New York: Plenum, 1982), Ch. 1; and Perkins, "Reshaping Technology in Wartime." For a previous treatment of herbicides, not based on primary documents, see Gail Peterson, "The Discovery and Development of 2,4-D," *Agr. Hist.,* 1967, *41:*243–253.

ing them. The onset of war evidently facilitated the removal of this conceptual block. Along with the interest lent this episode by the rich mixture of issues pertaining to simultaneous discoveries, discontinuous scientific progress through the rupture of conceptual barriers, and the impact of World War II on science and technology, the herbicide story is also significant in that it involves a field—plant physiology—as yet little studied by historians of science. The physiology of plant hormones was one of the most dynamic life science fields in the interwar years, yet it has been largely overlooked, perhaps because it was not among the sciences pursued at extension stations and other agricultural research institutions at this time.[3] Furthermore, in addition to the novelty of an archive- and courtroom record–based account of this episode for historians of science, this story draws further significance from important connections to historical issues beyond the usual domain of science and technology studies, issues concerning the relation of modernity to farming and to the natural world in general and the ecological consequences thereof. Many economists have observed that the very twentieth-century farming innovations that share roots with military technology—synthetic fertilizers, tractors, insecticides, herbicides—are among those largely responsible for transforming the farm from a cottage industry into something that resembles a mechanized factory, dependent much more on capital inputs than on skilled labor. Marxist scholars, in particular, have suggested that the innovations that since the later nineteenth century have led to the progressive dispossession of farmers from their traditional means of production have been introduced in the West, and propagated elsewhere, with the assistance of governments beholden to capitalist interests.[4] Nat-

[3] Robert K. Merton, "Singletons and Multiples in Scientific Discovery: A Chapter in the Sociology of Science," *Proceedings of the American Philosophical Society,* 1961, *105:*470–486; Thomas Kuhn, "The Historical Structure of Scientific Discovery," in *The Essential Tension* (Chicago: Univ. Chicago Press, 1977), pp. 165–177; Gaston Bachelard, *The New Scientific Spirit,* trans. Arthur Goldhammer (Boston: Beacon, 1984); and Mary Tiles, *Bachelard, Science, and Objectivity* (Cambridge: Cambridge Univ. Press, 1984). For historical treatments of plant sciences and agricultural research during the early twentieth century see Deborah Fitzgerald, *The Business of Breeding: Hybrid Corn in Illinois, 1890–1940* (Ithaca, N.Y.: Cornell Univ. Press, 1990); Diane Paul and Barbara Kimmelman, "Mendel in America: Theory and Practice, 1900–1919," in *The American Development of Biology,* ed. Ronald Rainger, Jane Maienschein, and Keith Benson (Philadelphia: Univ. Pennsylvania Press, 1988), pp. 281–310; Carroll Pursell, "The Administration of Science in the Department of Agriculture, 1933–1940," *Agr. Hist.,* 1968, *42:*231–240; Charles Rosenberg, "Rationalization and Reality in Shaping American Agricultural Research," in *The Sciences in the American Context: New Perspectives,* ed. Nathan Reingold (Washington, D.C.: Smithsonian Institution Press, 1979), pp. 143–164; Margaret Rossiter, "The Organization of the Agricultural Sciences," in *The Organization of Knowledge in Modern America, 1860–1920,* ed. Alexandra Oleson and John Voss (Baltimore: Johns Hopkins Univ. Press, 1979), pp. 211–248; and Wayne Rasmussen, *Taking the University to the People: Seventy-five Years of Cooperative Extension* (Ames: Iowa State Univ. Press, 1989). See also the contributions in David Danbom, ed., *Publicly Sponsored Agricultural Research in the United States, Agr. Hist.,* 1989, *62:*1–329, and in Alan Marcus and Richard Lowitt, eds., *The United States Department of Agriculture in Historical Perspective, ibid.,* 1990, *64:*1–331. For one of the few histories treating plant physiology see Linda Sage, *Pigment of the Imagination: A History of Phytochrome Research* (San Diego, Calif.: Academic, 1992).

[4] On the role of scientific research in the industrialization of agriculture during the twentieth century see Lawrence Busch and William Lacy, *Science, Agriculture, and the Politics of Research* (Boulder, Colo.: Westview, 1983); Jack R. Kloppenberg, Jr., *First the Seed: The Political Economy of Biotechnology, 1492–2000* (Cambridge: Cambridge Univ. Press, 1988); Deborah Fitzgerald, "Farmers Deskilled: Hybrid Corn and Farmers' Work," *Technol. Cult.,* 1993, *34:*324–343; John Perkins, "The Rockefeller Foundation and the Green Revolution, 1941–1956," *Agriculture and Human Values,* 1990, *7*(2):6–18; Perkins, *Geopolitics and the Green Revolution: Wheat, Genes, and the Cold War* (New York: Oxford Univ. Press, 1997); Richard Wines, *Fertilizer in America: From Waste Recycling to Resource Exploitation* (Philadelphia: Temple Univ. Press, 1985); Jim Hightower, *Hard Tomatoes, Hard Times* (Cambridge, Mass.: Schenckman, 1978); James Whorton, *Before "Silent Spring": Pesticides and Public Health in Pre-DDT America* (Princeton, N.J.: Princeton Univ. Press, 1974); and Thomas Dunlap, *DDT: Scientists, Citizens, and Public Policy* (Princeton, N.J.: Princeton Univ. Press, 1981). On the economics and ecology of current herbicide use see Sheldon Krimsky and Roger Wrubel, *Agricultural Biotechnology and the Environment* (Urbana: Univ. Illinois Press, 1996), Ch. 2. Though I will not address these issues

urally, in a short essay on the origin of herbicides there is not sufficient scope to address all of these connected issues systematically, but in what follows I will attempt to touch on all of them.

HORMONE RESEARCH IN 1920S AND 1930S PLANT PHYSIOLOGY

As already intimated, the first powerful, selective herbicides of the 1940s derived ultimately from the work of physiologists who studied plant hormones in the first decades of the twentieth century. In the 1910s and 1920s an influential school of plant physiology grew up around Friedrich Went in the Botanical Institute at the University of Utrecht, blazing a trail in hormone research by means of experimental methods that featured simple but carefully controlled bioassays and the precise mathematical analysis of data from them. The essential aim was to unravel the chemical mechanisms governing plant growth and development. Over two decades this group gradually showed that tropisms—for instance, the growth of plant shoots toward light—could be explained by specific chemical signals or hormones emanating from control centers such as the shoot apex. A landmark triumph of the Utrecht school was the 1926 isolation from shoot tips of the signaling substance, dubbed "auxin" (from the Greek *auxein,* "to enlarge"), in blocks of agar gel by Frits Went (1903–1990), son of the lab director. The substance in the agar, at first known only as a heat-resistant small chemical of molecular weight around 350 daltons, could fully substitute for the shoot tips of decapitated oat seedlings in permitting stem elongation, the direction of which depended on the distribution of the substance. The elongation of decapitated oat seedlings, used as a standard bioassay for the presence and relative quantity of auxin, opened the way to purification of sufficient quantities for chemical characterization. After failing to extract adequate yields of auxin from even 100,000 corn seedlings, Fritz Koegl, Went's biochemist collaborator from the Organic Chemistry Institute at Utrecht, turned to human urine, a standard source for purification of animal hormones, and in 1932 described the structure of a highly active molecule. Shortly afterward this same group announced the finding of another auxin of similar structure; then they identified a quite different third auxin, or "hetero-auxin" (as opposed to the first two, "auxin-a" and "auxin-b"), 3-indole acetic acid (or IAA). Koegl's group and others were able to isolate IAA from a variety of plants, and this molecule is now regarded as the chief natural auxin.[5]

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here, there are also implications of this story for the ecological crisis confronting modernity and the hostility toward nature embodied in our dealings with nature, as pointed out by Martin Heidegger and, more recently, by "Deep Ecology" theorists. See Michael Zimmerman, *Contesting Earth's Future: Radical Ecology and Postmodernity* (Berkeley: Univ. California Press, 1994); and Zimmerman, *Heidegger's Confrontation with Modernity: Technology, Politics, and Art* (Bloomington: Indiana Univ. Press, 1990). For an unusually thoughtful consideration of Heidegger's analogy between technological total warfare and modern farming see John Caputo, "Heidegger's Scandal: Thinking and the Essence of the Victim," in *The Heidegger Case: On Philosophy and Politics,* ed. Tom Rockmore and Joseph Margolis (Philadelphia: Temple Univ. Press, 1992), pp. 265–281.

[5] See Kenneth V. Thimann and Frits Went, *Phytohormones* (New York: Macmillan, 1937), for a comprehensive account of knowledge about auxin in the late 1930s; see also Theodor Weevers, *Fifty Years of Plant Physiology* (Amsterdam: Scheltema & Holkema, 1949), Ch. 8. On animal hormone research see Nelly Oudshoorn, "United We Stand: The Pharmaceutical Industry, Laboratory, and Clinic in the Development of Sex Hormones into Scientific Drugs, 1920–1940," *Science, Technology, and Human Values,* 1993, *18:*5–24; and Adele Clarke, "Research Materials and Reproductive Science in the United States, 1910–1940," in *Physiology in the American Context, 1850–1940,* ed. Gerald Geison (Baltimore: American Physiological Society, 1987), pp. 323–369. Whether Koegl's purification tactic indicated a belief that some growth hormones, like vitamins, are universal in both the plant and animal kingdoms need not concern us here; but see Ekkehard Hoxtermann, "Zur Geschichte des Hormonbegriffes in der Botanik und zur Entdeckungsgeschichte der 'Wochstoffe,'" *History and Philosophy of Life Science,* 1994, *16:*311–337. Koegl's findings are reported in Fritz Koegl, "Die Chimie

By the mid 1930s the new plant physiology in the Dutch style had strong footholds in several North American research institutions, including life science departments at the University of Chicago, Caltech, and Harvard, thanks in part to both the immigration of scientists and the training of Americans in Holland. The fact that the field was represented at elite universities like these, lacking in any major agricultural mission, bespeaks the importance of plant hormones as an area of basic biology at the time. Plant physiologists working on hormones studied fundamental phenomena of organic growth and development through interventionist experimentation and offered as one of the field's several justifications the ultimate possibility of power over those phenomena, much like the nascent "molecular biology" of the time (and many fields of life science today). As one leading plant physiologist put it in a meeting a few years later, early in World War II: "The ultimate objective of a considerable number of workers in the field of biology, is *growth control.* The familiar phrase that 'once normal growth is better understood it should be possible to control abnormal growth' is in the minds of all." Even more than genes, hormones were the interwar era's prime examples of "master molecules" (in Evelyn Fox Keller's phrase), the submicroscopic physical entities credited with the control of growth and other manifestations of life in plants and animals alike. Knowledge of these master molecules, hormone physiologists promised, was the key to controlling growth, and other vital phenomena, artificially.[6] While some plant physiologists in the 1930s devoted themselves to discovering new hormones and others concentrated on exploring auxin and its role in greater depth, the control of plant life through the manipulation of molecules was an implicit goal of both groups.

Among the main lines of auxin work were studies of the synthesis and transport of auxin in the plant, investigations of its mechanism of action, and research on the relationship of the hormone's chemical structure to reception and action in tissue. In this last line of research, one major approach involved the testing of synthetic IAA-like compounds in an effort to identify the molecular structures necessary for auxin activity. The most prominent group pursuing this work was at the Boyce Thompson Institute in Yonkers, New York, led by Percy Zimmerman (1884–1958), a broadly educated midwesterner trained in plant

des Auxins und sein Vorkommen im Pflanzen- und Tierreich," *Naturwissenschaft,* 1933, *21:*17–21; Koegl, Adrianus J. Haagen-Smit, and Hanni Erxleben, "Über ein neues Auxin aus Harn: Mitteilung über pflanzliche Wachstumsstoffe," *Zeitschrift für Physiologische Chemie,* 1934, *228:*90–103; and Koegl and D. G. Kostermans, "Über die Konstitutions-Spezifität des Hetero-auxins," *ibid.,* 1935, *235:*201–216. Auxin-a and auxin-b are today regarded as artifacts, evidently the result of fraud in Koegl's lab. For a brief historical overview see Peter Karlson, "Ectohormones and Phytohormones," *Trends in Biochemical Sciences,* 1982, *7:*382–383.

[6] George S. Avery, "Control of Growth and Differentiation in Plants," *Cold Spring Harbor Symposia in Quantitative Biology,* 1942, *10:*1–6, on p. 1. For another expression of hope that knowledge of plant hormones would provide the key to manipulating plant growth at will see Johannes van Overbeek, "Growth Regulating Substances in Plants," *Annual Review of Biochemistry,* 1944, *13:*631–666. On "master molecules" see Evelyn Fox Keller, "The Force of the Pacemaker Concept in Theories of Aggregation in Cellular Slime Mold," *Perspectives in Biology and Medicine,* 1983, *26:*515–521. Though this is beside the point for present purposes, it could be argued that hormone physiology constituted "molecular biology" in the late 1930s as much as did the molecular genetics research of biologists such as George Beadle, according both to contemporary usage of this ill-defined term and to definitions based on criteria like technological ambitions and epistemological style. On the biotechnological ambitions of molecular geneticists of the 1930s and 1940s see Keller, "Physics and the Emergence of Molecular Biology: A History of Cognitive and Political Synergy," *Journal of the History of Biology,* 1990, *23:*389–409; and Lily Kay, "Problematizing Basic Research in Molecular Biology," in *Private Science,* ed. Thackray (cit. n. 1), pp. 20–38. For questions about the identification of "molecular biology" with molecular genetics see Pnina Abir-Am, "Themes, Genres, and Orders of Legitimation in the Consolidation of New Scientific Disciplines: Deconstructing the Historiography of Molecular Biology," *Hist. Sci.,* 1985, *23:*73–117; Doris Zallen, "Redrawing the Boundaries of Molecular Biology: The Case of Photosynthesis," *J. Hist. Biol.,* 1993, *26:*65–87; and Rasmussen, "Midcentury Biophysics Bubble" (cit. n. 1).

biology by Otis Caldwell of the University of Chicago. Employing a strategy of inspired trial and error with compounds synthesized for him by chemist collaborators, testing each on whole plants as well as isolated stem segments, Zimmerman pushed the boundaries of "auxin" far beyond structures resembling IAA. In 1935 he found that molecules with double aromatic rings, such as naphthalene acetic acid (NAA), had strong auxin activity, and in 1942 he discovered a family of single-ring chlorinated phenoxy and benzoic acids that also had very high auxin activity in stem elongation assays, despite their even simpler structures. (See Figure 1.) Furthermore, some of these synthetic hormones, including the highly potent compound 2,4 dichlorophenoxyacetic acid (2,4-D), affected the morphology of developing organs (such as the pattern of leaf venation or the fusion of floral parts) in ways not found with natural hormones. (See Figure 2.) Possible applications to agriculture were explicitly at stake in Zimmerman's research, as reflected in the discussion sections of his experimental studies, by his publications devoted entirely to subjects like the use of aerosol spray methods with hormones, and by the patents regularly taken out by the Boyce Thompson on his work. Specific applications mentioned in the group's papers included the production of oversized flowers, the ripening of premature or seedless fruit, the prevention of fruit drop in orchards, and even the harnessing of the "morphogenetic properties" of synthetic hormones to produce crop plants altered in form—but the possibility of using growth regulators as herbicides was never raised in any publication or patent.[7]

Founded in 1924 by the eponymous philanthropist and friend of Herbert Hoover, who was convinced that improved farming would alleviate hunger and therefore promote peace, democracy, and social justice, the Boyce Thompson Institute was for half a century (until its move to Cornell University in the 1970s) perhaps the most prominent nonacademic research institution in the United States for basic work in fields such as plant pathology and plant physiology. The long-range humanitarian mission of the Boyce Thompson Institute, as well as its policy that patenting and licensing inventions to industry would both promote practical innovation and help fund research, helps explain the unusually high degree of attention to potential applications on Zimmerman's part. To the extent that practical applications were considered at all by plant physiologists elsewhere, the view that hormones might be used to stimulate or otherwise enhance crop plants was shared by the entire field in the 1930s, including those who studied hormones other than auxin—such as Johannes van Overbeek of Caltech, working on the cell-proliferation stimulators in coconut milk (later known as "cytokinin"), and James Bonner of Caltech, working on the wound hormone he called "traumatin" and on thiamin, which functions in plants as a "root hormone." (As the 1930s progressed, plant physiologists began to distinguish between "growth regulators" with hormone-like activity, such as Zimmerman's synthetics, and true hormones, defined as those endogenous growth regulators that naturally govern plant development, but in this essay I use the term "hormone" for both, in the colloquial fashion of the day.) By 1940, synthetic hormone products that enabled nurserymen to promote rooting of cuttings and orchardists to spray trees to prevent preharvest fruit drop

[7] Percy Zimmerman and Frank Wilcoxon, "Several Chemical Growth Substances Which Cause Initiation of Roots and Other Responses," *Contributions from Boyce Thompson Institute*, 1935, *7*:209–229; Zimmerman and Albert Hitchcock, "Formative Effects Induced with B-Phenoxyacetic Acid," *ibid.*, 1941, *12*:1–14; Zimmerman and Hitchcock, "Substituted Phenoxy and Benzoic Acid Growth Substances and the Relation of Structure to Physiological Activity," *ibid.*, 1942, *12*:321–343; Zimmerman, Hitchcock, and E. K. Harvill, "Xylenoxy Growth Substances," *ibid.*, 1944, *13*:273–280; and Zimmerman and Hitchcock, "The Aerosol Method of Treating Plants with Growth Substances," *ibid.*, pp. 313–322. On Zimmerman's background and research style see Hitchcock, "Percy W. Zimmerman," *ibid.*, 1960, *20*:1–5.

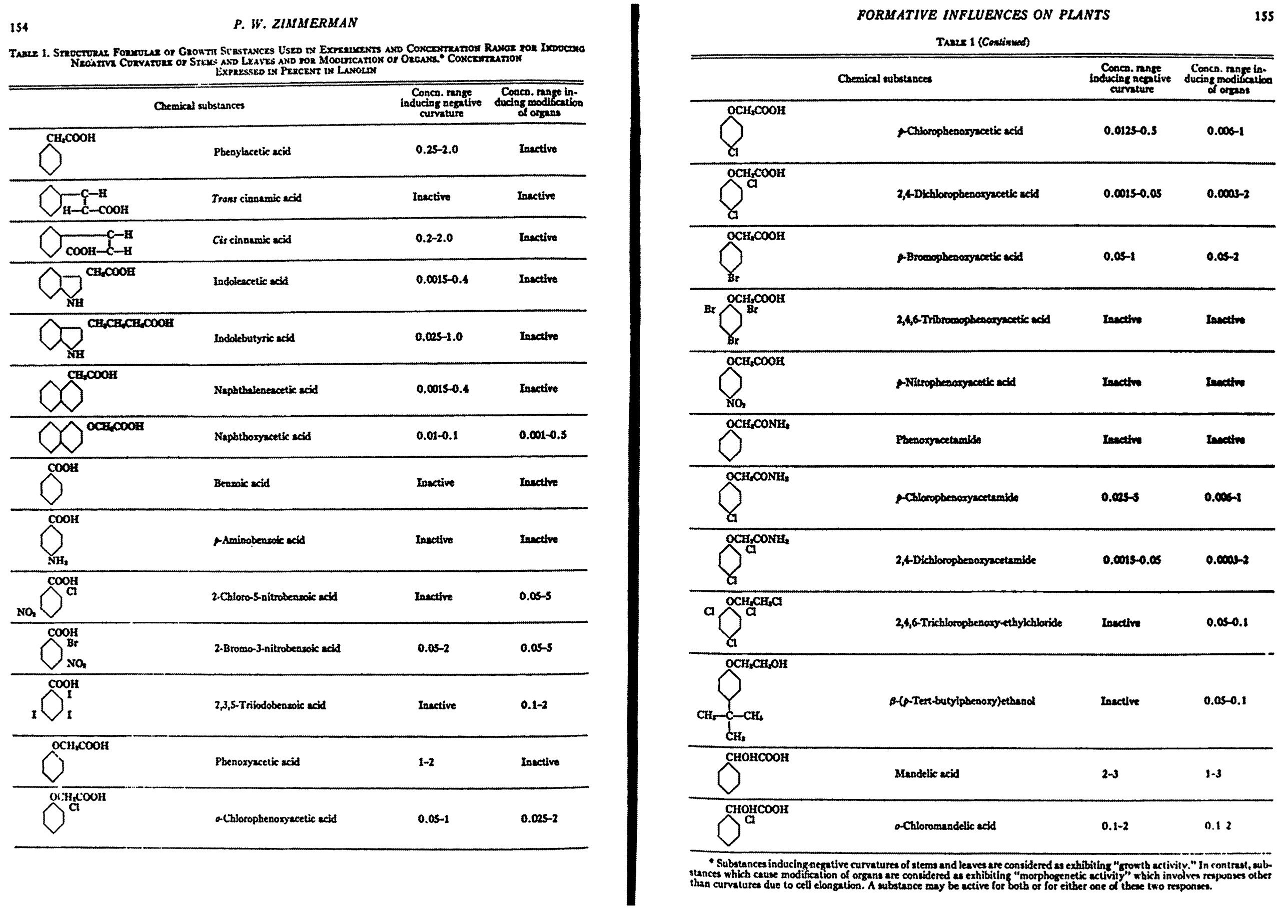

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TABLE 1. STRUCTURAL FORMULAS OF GROWTH SUBSTANCES USED IN EXPERIMENTS AND CONCENTRATION RANGE FOR INDUCING NEGATIVE CURVATURE OF STEMS AND LEAVES AND FOR MODIFICATION OF ORGANS.* CONCENTRATION EXPRESSED IN PERCENT IN LANOLIN

Chemical substances	Concn. range inducing negative curvature	Concn. range inducing modification of organs
Phenylacetic acid	0.25–2.0	Inactive
Trans cinnamic acid	Inactive	Inactive
Cis cinnamic acid	0.2–2.0	Inactive
Indoleacetic acid	0.0015–0.4	Inactive
Indolebutyric acid	0.025–1.0	Inactive
Naphthaleneacetic acid	0.0015–0.4	Inactive
Naphthoxyacetic acid	0.01–0.1	0.001–0.5
Benzoic acid	Inactive	Inactive
p-Aminobenzoic acid	Inactive	Inactive
2-Chloro-5-nitrobenzoic acid	Inactive	0.05–5
2-Bromo-3-nitrobenzoic acid	0.05–2	0.05–5
2,3,5-Triiodobenzoic acid	Inactive	0.1–2
Phenoxyacetic acid	1–2	Inactive
o-Chlorophenoxyacetic acid	0.05–1	0.025–2

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TABLE 1 (*Continued*)

Chemical substances	Concn. range inducing negative curvature	Concn. range inducing modification of organs
p-Chlorophenoxyacetic acid	0.0125–0.5	0.006–1
2,4-Dichlorophenoxyacetic acid	0.0015–0.05	0.0003–2
p-Bromophenoxyacetic acid	0.05–1	0.05–2
2,4,6-Tribromophenoxyacetic acid	Inactive	Inactive
p-Nitrophenoxyacetic acid	Inactive	Inactive
Phenoxyacetamide	Inactive	Inactive
p-Chlorophenoxyacetamide	0.025–5	0.006–1
2,4-Dichlorophenoxyacetamide	0.0015–0.05	0.0003–2
2,4,6-Trichlorophenoxy-ethylchloride	Inactive	0.05–0.1
β-(*p*-Tert-butylphenoxy)ethanol	Inactive	0.05–0.1
Mandelic acid	2–3	1–3
o-Chloromandelic acid	0.1–2	0.1 2

* Substances inducing negative curvatures of stems and leaves are considered as exhibiting "growth activity." In contrast, substances which cause modification of organs are considered as exhibiting "morphogenetic activity" which involves responses other than curvatures due to cell elongation. A substance may be active for both or for either one of these two responses.

Figure 1. *Auxin (i.e., elongation-inducing) and formative (morphogenetic) activities of natural hormones (indoleacetic acid) and auxin-like synthetic plant-growth regulators. From P. W. Zimmerman, "Formative Influences of Growth Substances on Plants,"* Cold Spring Harbor Symposia in Quantitative Biology, *1942,* 10:*152–159; used with permission.*

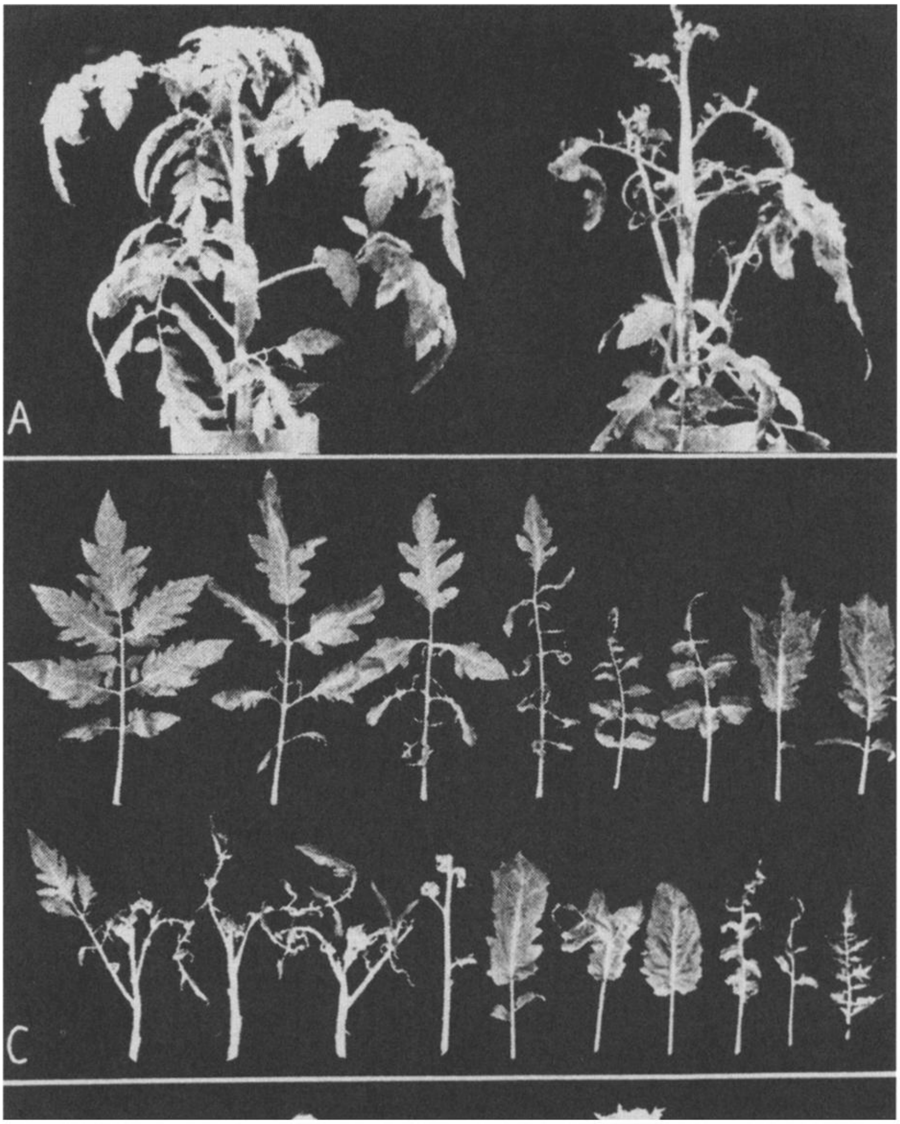

Figure 2. *Toxic and formative effects of 2,4-D on tomato plants.* Top: *Plant damaged by exposure to trace quantities of 2,4-D aerosol (right), compared with unexposed plant (left).* Bottom: *Morphogenetic influence of low 2,4-D doses on leaf development (upper left is unexposed control). From P. W. Zimmerman, "Formative Influences of Growth Substances on Plants,"* Cold Spring Harbor Symposia in Quantitative Biology, *1942,* 10:*152–159; used with permission.*

were available commercially—many based on Boyce Thompson patents. These products too were an outgrowth of the mind-set that hormones, especially synthetic growth regulators improving on nature, might stimulate crop plants to higher productivity.[8]

[8] On the history of Boyce Thompson and his institution see William Crocker, *Growth of Plants: Twenty Years' Research at Boyce Thompson Institute* (New York: Reinhold, 1948); Hermann Hagedorn, *The Magnate: William*

In the 1930s the obstacles to conceiving of hormones as herbicides were as much institutional as theoretical. Hormones were not much studied by biologists at experiment stations and similar agricultural research institutions, while weed control, which was a focus of attention there, was not the domain of plant physiologists. Rather, weed-control agronomists and ecologists studied how to prevent pest plant infestations through containment and labor-intensive weed-eradication campaigns—or, when pest plants were irreversibly established, how to reduce their economic impact through ecological interventions such as cultural control (strategic planting, special technique plowing, harrowing, etc.) and biological control. There were a few physiologists, such as Alden Crafts of the University of California, pursuing the development of chemical weed killers, especially after the successful mid-1930s introduction of the selective herbicide dinitro-o-cresylate (trade named Sinox) for grain production. However, Crafts felt himself a lonely prophet, complaining in 1943 that he had "tried for years to interest [the United States Department of Agriculture (USDA)] . . . in chemical weed control," without avail. Even Crafts's own 1942 textbook on weed control, showcasing the latest herbicide research of himself and his California colleagues, spends only about thirty pages on the use of selective chemical weed killers, roughly the same amount of space devoted to cultural and biological control. The bulk of the textbook describes then-mainstream approaches to destroying weeds in infested local areas, primarily nonselective methods such as fire and total soil sterilization with inorganic toxins. In his own research program on selective herbicides, Crafts's approach was a trial-and-error exploration of the toxicity of dyestuffs, especially compounds related to the dangerously explosive and poisonous Sinox. Hormones played no evident role in his research. It seems that, before World War II, little relation was perceived between poisons like Sinox and plant hormones, even by the plant physiologists most concerned with weed control (the exception is one group at Du Pont, whose work was largely neglected, as I will soon relate).[9]

One of the several independent discoverers of 2,4-D's utility as an herbicide was Ezra J. Kraus (1885–1960), head of botany at the University of Chicago. (See Figure 3.) Research in his department, equipped with the finest greenhouses and environmental control facilities of its day (thanks in part to generous Rockefeller Foundation funding), revolved generally around the interaction of external conditions and endogenous hormones in shaping plant growth. Students and ideas flowed rather freely between Chicago and the new research facility of the USDA Bureau of Plant Industry (BPI) in Beltsville, Maryland, which Kraus, as a USDA consultant, had helped design. Kraus carried out some of his

Boyce Thompson and His Times (New York: Reynal & Hitchcock, 1935); and http://birch.cit.cornell.edu/ar98/history. On Bonner and thiamin see Nicolas Rasmussen, "The Forgotten Promise of Thiamin: Merck, Caltech Biologists, and Plant Hormones in a 1930s Biotechnology Project," *J. Hist. Biol.*, 1999, *32*:245–261. See also van Overbeek, "Growth Regulating Substances in Plants" (cit. n. 6).

[9] On Crafts's thinking about chemical weed control and his perceived difficulty in promoting it see, e.g., Alden Crafts to Ezra J. Kraus, 4 Jan. 1943, 14 Jan. 1943 (quotation), 23 Jan. 1943, in Botany Department Papers, University of Chicago Archives (hereafter cited as **Botany Dept. Papers, Univ. Chicago**), box 7, unlabeled folder. For the textbook see Wilfred Robbins, Alden Crafts, and Richard Raynor, *Weed Control* (New York: McGraw-Hill, 1942); see also John Fogg, *Weeds of Lawn and Garden* (Philadelphia: Univ. Pennsylvania Press, 1945). On New Deal era agricultural programs see Christina Campbell, *The Farm Bureau and the New Deal* (Urbana: Univ. Illinois Press, 1962); and Richard Kirkendall, *Social Scientists and Farm Politics in the Age of Roosevelt* (Columbia: Univ. Missouri Press, 1966). For examples of drug development procedures in the early twentieth century see Timothy Lenoir, "A Magic Bullet: Research for Profit and the Growth of Knowledge in Germany around 1900," *Minerva*, 1988, *26*:66–88; and John Lesch, "Chemistry and Biomedicine in an Industrial Setting: The Invention of the Sulfa Drugs," in *Chemical Sciences in the Modern World*, ed. Seymour Mauskopf (Philadelphia: Univ. Pennsylvania Press, 1993), pp. 158–215.

Figure 3. *Ezra Kraus, chairman of the botany department at the University of Chicago, circa 1930. Courtesy of the Library of the University of Chicago.*

research in Beltsville; some Chicago Ph.D. students did their theses on USDA projects; and a number of Chicago graduates filled the permanent jobs becoming available at the growing institution. One Chicago graduate and Kraus student was John Mitchell (1905–1992), who in 1938 became a senior BPI plant physiologist and coinvestigator with Kraus on several USDA grants. During the late 1930s Kraus spent several months each year in Beltsville overseeing this collaborative research, which involved three main lines of work: efforts to use light exposure to manipulate crop growth and to isolate the hypothesized hormone controlling a plant's flowering in response to day length; efforts to isolate the transforming factor, hypothesized at the time as a new de-differentiation hormone, by which the microbe *Agrobacterium tumefaciens* causes growths on infected plants; and, in cooperation with Bonner and Frits Went, now at Caltech, more detailed exploration of auxin activity in plant development. Thus Kraus himself was a key conduit bringing the new physiology of plant hormones to agricultural research. Through 1940 his auxin studies at BPI seem to have concentrated on the role of this hormone in growth, differentiation of organs, and flowering of crop plants. Kraus's vision for Beltsville's future then featured isolating "additional hormones for specific purposes" of growth control, continuing study of how various environmental conditions affect hormone response, and even investigating how the mechanism of hormonal growth promotion in plants might "throw some light on human cancer." But again, despite his entrepreneurship on behalf of hormones in plant biology and agriculture, Kraus never suggested using hormones as plant killers.[10]

HORMONES AT WAR

The onset of World War II mobilized many USDA and other agricultural scientists to undertake projects relevant to the war effort, primarily by studying ways to increase the efficiency of food production (although USDA scientists would also contribute to wartime medical projects, including penicillin and antimalarial drug development, as well as disease control with DDT). But this was not the way herbicides were brought into being by Kraus and his USDA collaborators. Hormone herbicides were developed as weapons, not as aids to agricultural or medical industry. From its inception in 1940 Kraus was a member of the National Academy of Sciences (NAS) top-secret committee on biological and chemical warfare—called in its several incarnations the WBC Committee, the ABC Committee, and, ultimately, the DEF Committee—which managed research for George Merck (pharmaceutical executive and close friend of Vannevar Bush), the government's chief of this work. Barely a week after the Japanese attack on Pearl Harbor, in December 1941, Kraus had drawn up an informal proposal to put his expertise to work in the war effort by

[10] For hormone work in Kraus's botany department at Chicago see, e.g., John W. Mitchell and William S. Stewart, "Comparison of Growth Responses Induced in Plants by Naphthalene Acetamide and Naphthalene Acetic Acid," *Botanical Gazette,* 1939, *101:*410–427; Karl C. Hamner and James Bonner, "Photoperiodism in Relation to Hormones as Factors in Floral Initiation and Development," *ibid.,* 1938, *100:*388–431; and Bonner autobiography, pp. 121–124, James Bonner Papers, California Institute of Technology Archives (hereafter cited as **Bonner Papers**), box 26. On later work at Chicago geared to manipulating plant growth see Horton Laude, "Combined Effects of Potassium Supply and Growth Substances on Plant Development," *Bot. Gaz.,* 1941, *103:*155–167; Daphne Swartz, "Effect of Various Growth-Regulating Substances upon Several Species of Plants," *ibid.,* pp. 366–373; and Charles Hamner, "Physiological and Chemical Responses of Bean and Tomato Plants to Alpha Naphthalene Acetamide and Phenylacetic Acid," *ibid.,* pp. 374–385. On the development of USDA research in the period see Pursell, "Administration of Science in the Department of Agriculture" (cit. n. 3). For Chicago work at Beltsville see Ezra J. Kraus, n.d. [1939], "SRF-2-45: Studies of Plant Hormones," and "SRF-2-15: Anatomical, Plant Physiological, and Biophysical Studies . . . , " in Botany Dept. Papers, Univ. Chicago, box 7, folder "Schoenhals Correspondence." See also Kraus, n.d. [1940], 1939–1940 progress report for "Project 9245," Botany Dept. Papers, Univ. Chicago, box 7, folder "Progress Reports."

developing plant hormone treatments that would damage crops and vegetation useful to the enemy: "Release of growth destroying substances . . . over rice fields would be a feasible and comparatively simple means of destruction of rice crops, the staple food supply of the Japanese. Distribution of sprays or mists over enemy forests would, through killing of trees, reveal concealed military depots. These are examples of many obvious military uses of these compounds." Kraus reportedly conceived of the idea of using hormone overdoses as herbicides on his own earlier in 1941. Though this claim would become controversial after the war, once intellectual property considerations put millions of dollars in the balance, there is no evidence whatsoever that he was aware of any others pursuing the same idea independently before 1945. At any rate, for the official WBC Committee report of February 1942, Kraus had formalized his ideas as a proposed military research contract; his project was given the go-ahead, together with more than a dozen other biological warfare projects ranging from the production of anthrax spores and the development of vaccines to protect Americans from anthrax to the cultivation of the late potato blight microbe (presumably for deployment against German potatoes).[11]

Kraus and Mitchell set to work growing rice in tanks and testing the killing power of both hormones and traditional inorganic poisons such as arsenic. In August 1943 the members of the NAS biological and chemical warfare committee who were concerned with economic war against the Japanese rice crop held a conference to discuss their first year and a half of progress. Entomologists reported the effects of various insects on rice plants grown under controlled conditions, mycologists reported the effects of fungi, and Kraus reported the effects of hormones and inorganic toxins. In their tank-grown rice plants, Kraus's team had found that the synthetic auxins NAA and phenylacetic acid were moderately effective as toxins and that monochlorophenoxyacetic acids were an order of magnitude more lethal. His tone was not sanguine, however; although application in powder, in aerosol, and in liquid vehicles directly to the water in the tanks had been tried, all methods were less effective in killing mature rice plants protected by a thick sheaf of leaves. At this point both Kraus and the NAS committee concluded that, given the unpredictable effectiveness of spraying and the huge doses of hormones often needed to kill rice, inorganic poisons such as thallium were more promising, as was biological warfare using certain fungal diseases. Kraus was still playing the scientific entrepreneur, trying imaginatively to find new uses for his hormones, with at least as much enthusiasm as he brought to his official role as a contractor charged with developing herbicides to wipe out crops and other vegetation. But in early 1944 Kraus's devotion to hormones and his wartime duties as an herbicide researcher finally meshed.[12]

[11] Ezra J. Kraus, "Plant Growth Regulators: Possible Uses," 18 Dec. 1941; and Kraus, "Project: Plant Growth Regulating Substances," 3 Feb. 1942 (quotation): "Report of WBC Committee, February 17, 1942," in Chemical and Biological Warfare files, United States National Academy of Sciences Archives, Washington, D.C. (hereafter cited as **Chemical and Biological Warfare Files**), Ser. 1, box 1, folder "WBC Committee Report, Exhibit F (III, Plants)." See also "DEF Committee: Present Status of Research Projects Initiated by War Research Service," 12 Oct. 1944, Botany Dept. Papers, Univ. Chicago, box 7, folder 2. On agriculture and agricultural research in the war effort see *Agriculture's Part in the War* (Washington, D.C.: USDA Office of Information, 1944). On penicillin see Neushul, "Science, Government" (cit. n. 1). On DDT and antimalarials see E. C. Andrus *et al.*, eds., *Advances in Military Medicine* (Boston: Little-Brown, 1948), Pts. 6, 8; and Perkins, "Reshaping Technology in Wartime" (cit. n. 1). On the U.S. biological and chemical warfare research program during World War II, a topic as yet little studied owing largely to official secrecy restrictions, see Barton Bernstein, "America's Biological Warfare Program in the Second World War," *Journal of Strategic Studies,* 1988, *11*:292–313; and Gerard Fitzgerald, "Engineering Biological Weapons: James Reyniers and the Technology of Isolation," paper presented at Joint Atlantic Seminar in the History of Biology, 1 Apr. 2000, Princeton University, Princeton, N.J.

[12] Kraus report, in minutes of conference held at the National Academy, 24 Aug. 1943, Chemical and Biological

Requisitions to chemical companies—including orders to the American Chemical Paint Company for 2,4-D and 2,4,5 trichlorophenoxyacetic acid (2,4,5-T), a related, highly active synthetic auxin—show with certainty that by February 1944 Kraus's team was expanding the range of hormones tested for their killing properties. Interestingly, in the light of his August 1943 report to the NAS, which did not mention the compounds, after the war Kraus would present documentary evidence and testimony that he had requested 2,4-D from Zimmerman in March 1943 and had ordered samples of 2,4-D, 2,4,5-T, and other chlorinated synthetic hormones from the Sherwin-Williams Chemical Company in August and September 1943.[13] Perhaps Kraus did not test the compounds immediately upon receipt. In any event, an internal report written by Mitchell in Beltsville and sent to Kraus shows that, in a test begun on 13 February 1944, dramatic killing was obtained with 2,4-D and 2,4,5-T sprayed in organic solvents on tomato plants. Greenhouse testing continued into the spring, when outdoor testing commenced; by July 1944 Kraus had confirmed through a colleague in the Chicago pharmacology department that 2,4-D had low toxicity to mice. In the summer of 1944 Mitchell and his fellow Beltsville plant physiologist Paul Marth found that 2,4-D had a selective effect on dandelions and other broadleaf weeds in grass lawns; thus Kraus was already involving his USDA collaborators in efforts to find nonmilitary, agricultural uses for these herbicidal hormones. At about the same time Charles Hamner, a former Chicago student who had just moved to the Cornell experiment station from Beltsville, showed with a colleague that 2,4,5-T was effective against certain common agricultural weeds such as bindweed (wild morning glory). Hamner's project acknowledged funding from Sherwin-Williams, indicating clearly that the chemical firm was exploring the potential of the same synthetic hormones being used in the government's secret research (informed almost certainly through Kraus and perhaps via Hamner—or simply through his order from the firm). With remarkable dispatch, the Cornell group published a preliminary report in *Science* in August 1944, and Kraus published their full results side by side with the equally unwarlike finding of the Beltsville group in the December 1944 issue of *Botanical Gazette,* of which he was chief editor. Both of these papers cite correspondence with Kraus in 1941 as the source of the idea that hormones could be used for selective weed control. Plainly, by this point Kraus—like Sherwin-Williams, the largest manufacturer of agricultural chemicals in the United States at the time—recognized the agricultural potential of 2,4-D and 2,4,5-T as herbicides and may have been seeking to establish an early priority date for conceiving of this application.[14] The fact that Kraus and

Warfare Files, Ser. 2, box 4, folder "Conferences: Rice Problem 1943"; and George Merck to J. M. Hutchins (cc Kraus), 7 Apr. 1944, and attached "Contract No. 39," Botany Dept. Papers, Univ. Chicago, box 7, folder "Confidential War Work."

[13] E. B. Fred to Kraus, 11 Jan. 1943; Ezra J. Kraus, "Affidavit of E. J. Kraus," 22 Jan. 1947; and Counsel for Plaintiff (Sherwin-Williams), "Dates to Be Relied upon by Plaintiff . . . Work at the Sherwin-Williams Company," 12 May 1947: records of Civil Action 850, *Sherwin-Williams Chemical Co. v. American Chemical Paint Co.,* Federal District Court of Delaware (hereafter cited as **Civil Action 850**), held at National Archives and Records Administration Regional Storage Facility, Philadelphia. See also chemical requisitions in Botany Dept, Papers, Univ. Chicago, box 7, folder "Confidential War Work."

[14] John W. Mitchell, "Aerosol Tests," 13 Feb. 1944, Botany Dept. Papers, Univ. Chicago, box 7, no folder (internal report); Graham Chen to Kraus, 6 July 1944, Botany Dept. Papers, Univ. Chicago, box 7, folder 1 (low toxicity to mice); Charles Hamner and H. B. Tukey, "The Herbicidal Action of 2,4 Dichlorophenoxyacetic and 2,4,5 Trichlorophenoxyactetic Acid on Bindweed," *Science,* 1944, *100:*154–155; Paul Marth and Mitchell, "2,4 Dichlorophenoxyacetic Acid as a Differential Herbicide," *Bot. Gaz.,* 1944, *106:*224–232; and Hamner and Tukey, "Selective Herbicidal Action of Midsummer and Fall Applications of 2,4-Dichlorophenoxyacetic Acid," *ibid.,* pp. 232–245. See also "Dates to be Relied upon by Plaintiff . . . Work at the Sherwin-Williams Company." That the contract between the University of Chicago and the U.S. government covering Kraus's war work (cit. n. 12) stipulates that patent rights for any inventions could, unless prohibited for security reasons, be claimed

Mitchell were working under a top-secret military contract must have made establishing scientific credit and patent priority rather difficult, though secrecy was obviously not an overwhelming inhibition.

In July 1944 the military weed-control project was officially transferred to the Chemical Warfare Service facility at Camp Detrick, Maryland, with Kraus still acting as advisor. For the next year A. G. Norman and a group of military scientists there conducted trials with various methods for applying herbicides and, with specially developed biological assays, tested over a thousand synthetic compounds for their potency as plant growth regulators and herbicides. The herbicides were not deployed against an enemy by the military until Viet Nam (as Agent Orange, whose active ingredients were 2,4-D and 2,4,5-T), although the Navy contracted with Sherwin-Williams for 2,000 tons of 2,4-D in August 1945, possibly for clearing bases. Naturally, the military research on herbicides was not published until after the war was finished. Indeed, in January 1945, even though—or perhaps because—Kraus himself was one of the chief offenders, the WBC security office gave him the job of censoring the plant physiology literature so that no new publications on the herbicidal properties of hormones would further breach security. The editors of plant physiology journals and the heads of agricultural research stations were mailed a letter from the National Research Council instructing them to send submitted articles dealing with plant hormones to Kraus for his approval. Kraus evidently felt a little awkward in the role, charged with censoring the work of his students and colleagues that he had so recently been trumpeting. For instance, in May 1945 he apologetically delayed publication of another paper by the Cornell group—this one acknowledging the support of Dow Chemical, which strongly suggests that this firm, too, was already alert to the commercial potential of 2,4-D.[15] For nearly a year, however, he dutifully prevented the appearance of further scientific publications dealing with the herbicidal effects of synthetic hormones.

MULTIPLE DISCOVERERS

While Kraus's herbicide project was proceeding under top-secret biological and chemical warfare auspices, plant physiologists at other laboratories were independently discovering the weed-killing power of 2,4-D and similar synthetic auxins. One was Vernon Stoutmeyer (1905–1992), a plant physiologist working at the USDA Plant Introduction Facility at Glen Dale, Maryland. Stoutmeyer reportedly first imagined that hormones might make useful herbicides in late 1941, after hearing a lecture by Kraus in Maryland in which the toxicity of the substances at high doses was a major theme. Though weed control had nothing to do with his official duties, Stoutmeyer's self-professed loathing of weeds had led him, on his own initiative, to test whether hormones might amplify the killing power

by the university perhaps explains Kraus's efforts to have the agricultural results published and credited to himself.

[15] "DEF Committee: Present Status of Research Projects" (cit. n. 11). For the wartime results of the Camp Detrick group see H. E. Thompson, Carl P. Swanson, and A. G. Norman, "New Growth Regulating Compounds, I: Summary of Growth-Inhibitory Activities of Some Organic Compounds as Determined by Three Tests," *Bot. Gaz.*, 1946, *107:*476–507; and other papers published as a special section of the June 1946 *Bot. Gaz.* On the Navy contract see "Dates to Be Relied upon by Plaintiff . . . Work at the Sherwin-Williams Company." On censoring the plant physiology literature see William B. Sarles to Kraus, 24 Jan. 1945, Botany Dept. Papers, Univ. Chicago, box 7, folder "Censorship." See also H. B. Tukey to Kraus, 26 Apr. 1945, with accompanying manuscript "The Comparative Potency of Several Growth-Regulating Substances in Combination with Various Carriers, with Special Reference to Their Herbicidal Value"; and Kraus to Tukey, 23 May 1945: Botany Dept. Papers, Univ. Chicago, box 7, in loose envelopes.

of standard inorganic poisons. Stoutmeyer soon found that some of his hormone-only controls also showed toxicity, and, having achieved some success in killing weeds with high doses of phenylacetic acid and naphthalene acetic acid, in early 1942 he communicated his findings to USDA scientists whose official responsibilities did include weed control. Later, after reading Zimmerman's mid-1942 paper on the high activity of 2,4-D and other phenoxy synthetic auxins, Stoutmeyer wrote Zimmerman to obtain samples of the compounds. He quickly discovered the potent killing action of 2,4-D on direct application to problematic woody weeds like mesquite and Japanese honeysuckle: in November 1942 he ordered another batch of 2,4-D, custom-made from a commercial supplier, with which he confirmed his preliminary findings on a range of pest plants before returning to the plant introduction research that was his job. Stoutmeyer's reports on the new class of weed killer may have died as they worked their way through USDA channels, or they may have been passed on to the group doing Kraus's military project at Beltsville after they were communicated to the Bureau of Plant Industry chief in September 1943.[16]

Other plant biologists who could—and after the war in fact did—contest the priority of Kraus and his circle worked in two groups in England: one at Rothamstead Experimental Station and the other with Imperial Chemical (ICI). Both groups were pursuing more traditional agricultural research programs—that is, investigations of methods aimed at increasing crop production. The ICI group found in 1940 that NAA had a selectively toxic action against broadleaf weeds in oat fields and that its use could increase grain yields. Then, evidently through a cooperative arrangement that involved communication of research results from Du Pont (whose activities I will discuss shortly), they found in field tests with 2,4-D and the closely related compound 4-chloro-2-methylphenoxyacetic acid conducted in 1941 and 1942 that both had more potency than NAA but similar action; this work resulted in a 1941 British patent application on the latter herbicide (trade name Methoxone). In November 1942 ICI filed a report on the herbicidal uses of these synthetic hormones with Britain's Agricultural Research Council. Also reported to the Agricultural Research Council that month was the independent work of the Rothamstead group, which had found that 2,4-D persisted long enough in soil to be used as a broadleaf weed killer and growth suppressor. In November 1942 these two groups were asked by British defense authorities to collaborate in investigating further productivity-enhancing and possible military applications of the synthetic hormones and were barred from publishing their findings until April 1945, at which time several sets of results appeared in the same issue of *Nature*. British sources allege that the findings of the British teams were communicated to the chemical warfare authorities in the United States at the beginning of 1944, although Kraus would claim that he never heard of their work before the 1945 publications, despite the presence of British liaison people on the DEF Committee. The British researchers were plainly irritated that they had been forbidden to publish while American academics had

[16] Vernon Stoutmeyer to F. C. Bradford, 26 Jan. 1942; Stoutmeyer to Henry Hopp, 17 Apr. 1942; Stoutmeyer, "Preliminary Report on the Use of Plant Growth Substances with Herbicides," Dec. 1942; Stoutmeyer to Percy Zimmerman, 6 Aug. 1942; Zimmerman to Stoutmeyer, 14 Aug. 1942, 26 Sept. 1942; Stoutmeyer lab notebook, experiments begun 24 Sept. 1942, 7 Oct. 1942, and 11 Nov. 1942; Stoutmeyer purchase order to American Chemical, 17 Nov. 1942, and receipt of 10 Dec. 1942; B. Y. Morrison to Robert Slater, 6 Sept. 1943 (Plaintiff's Exhibits P-130, 132, 146, 133, 135, 138, 139, 140, 143, and 147, respectively); and deposition of V. T. Stoutmeyer, 23 April 1947, pp. 4–23: records of *Dow Chemical Co. v. American Chemical Paint Co.*, Civil Action 5760, Eastern Michigan District Federal Court (hereafter cited as **Civil Action 5760**), held at Detroit National Archives and Records Administration Records Facility, Chicago.

not been prevented from establishing apparent priority in 1944.[17] This dispute aside, ICI was certainly influenced by studies conducted by Du Pont, while Du Pont (and probably the Rothamstead group as well) owed its inspiration to the work of Percy Zimmerman. Thus, with respect to this work—as in the cases of Stoutmeyer and Kraus—Zimmerman and his synthetic auxin research can be regarded as the ultimate source of selective hormone herbicides, even if Zimmerman himself did not imagine this use of his compounds.

As my references to Du Pont have hinted, American industrial scientists also figured among the contenders for priority in the discovery of the herbicidal effectiveness of 2,4-D. Indeed, in 1946–1947 a number of firms entered into fierce litigation over intellectual property that mirrored the priority dispute simultaneously occurring among Kraus and other researchers. Among these firms, Du Pont provided especially solid evidence that its scientists had independently—and almost certainly first—discovered the herbicidal powers of 2,4-D. The Du Pont effort had begun in October 1936 when the plant pathologist Wendell Tisdale, manager of Du Pont's Pest Control Research Division, attended a talk by Zimmerman on the structure and uses of synthetic plant hormones, especially indole derivative compounds. The following day Tisdale sent a memo to several other Du Pont managers; it described Zimmerman's findings, noted that some of the more powerfully stimulatory chemicals were lethal at high concentrations, and asked whether Du Pont had any of the indole compounds on hand for testing as insecticides or fungicides. Why not test them on plants as well, suggested Tisdale, to see if any could be useful as weed killers? Other Du Pont research managers had also been excited by Zimmerman's talk and by the promise of synthetic hormones for agriculture. Soon a program of chemical synthesis and testing on plants, with the primary goal of discovering new, patentable plant growth stimulators, was launched. Significantly, a policy was also established that any compounds that caused damage to plants in these tests, or in tests involving plants in existing fungicide and insecticide discovery programs, should be submitted for further investigation as possible herbicides.[18]

In mid 1937 Du Pont had its plant hormone discovery program under way, with John Lontz in the Experimental Station's chemical department in charge of synthesizing candidate hormones and Hubert Guy in the biological department in charge of testing—mainly by painting the compounds in lanolin suspension on one side of a young tomato plant's stalk and checking for bending or other growth responses. Lontz's mid-1941 progress report on the project listed a number of highly active halogenated phenoxy compounds: a dozen with strong formative activity and about the same number with high toxicity had been found. In the first category, 2,4-D was described as one of the most promising com-

[17] R. E. Slade, W. G. Templeman, and W. A. Sexton, "Plant-Growth Substances as Selective Weed-Killers," *Nature,* 1945, *155:*497–498; P. S. Nutman, H. G. Thornton, and J. H. Quastel, "Inhibition of Plant Growth by 2:4-Dichlorophenoxyacetic Acid and Other Plant-Growth Substances," *ibid.,* pp. 498–500; G. E. Blackman, "A Comparison of Certain Plant-Growth Substances with Other Selective Herbicides," *ibid.,* pp. 500–501; and Sexton, Slade, and Templeman, British Patent no. 573,929, application date 7 Apr. 1941. On the cooperative arrangements between ICI and Du Pont see David Hounshell and John K. Smith, *Science and Corporate Strategy: Du Pont R & D, 1902–1980* (Cambridge: Cambridge Univ. Press, 1988), Ch. 10. For private accounts of wartime events see Zimmerman to James Bonner, 12 Dec. 1952; W. G. Templeman to Bonner, 17 Jan. 1953; J. H. Quastel to Bonner, 12 Jan. 1953; and Kraus to Robert Bandurski, 22 Dec. 1952: Bonner Papers, box 11, folder "History of 2,4 D." For a published example of English attitudes see the comments in Blackman, K. Holly, and H. A. Roberts, "The Comparative Toxicity of Phytocidal Substances," *Symposia of the Society for Experimental Biology,* 1949, *3:*283–317.

[18] W. H. Tisdale to P. L. Salzburg, 22 Oct. 1936; G. D. Patterson to P. Coolidge, 22 Oct. 1936; Salzburg to Tisdale, 27 Oct. 1936; and Salzburg to Coolidge, 27 Oct. 1936 (Plaintiff's Exhibits P-104, 119, 114, and 115, respectively): Civil Action 5760.

pounds for preventing preharvest apple drop in orchards; several others showed promise for the production of seedless fruit. The report, which recommended a broad patent application on the use of this class of compounds as growth regulators, made no specific mention of using any as weed killers. After an interruption when Guy left the firm, another, more systematic program of testing compounds specifically for herbicidal ability commenced. In early 1942 the team found that monochlorophenoxyacetates were especially lethal; soon, however, all the researchers were reassigned to tasks more relevant to Du Pont's role in the war effort.[19] At this point the firm drew up a patent application, in Lontz's name, covering 2,4-D as well as 2,4,5-T and other halogenated phenoxy acids for use as plant growth regulators. The patent, awarded in 1943, was quite broad in its scope, naming many synthetic growth-regulating compounds and claiming a variety of uses, from preventing fruit and leaf drop from trees to stimulating root formation in the propagation of cuttings. Du Pont did not, however, list weed killing as an application for the new synthetic hormones, a point later made much of in court by the chief rival claimant, American Chemical Paint Company. Du Pont witnesses like Tisdale did what they could to portray the firm's prewar quest for weed killers as a high priority, although the content of the key Lontz patent of course suggested the opposite.[20] Most likely, the challenge from American Chemical made Du Pont appreciate the value of Tisdale's insights and Lontz's findings anew. Du Pont's oversight is further evidence of the power of the mind-set that hormones were for *enhancing* the growth of plants, evidence that seems especially striking given that the research managers for whom Lontz worked had unambiguously ordered a search for novel weed-killing compounds.

Though a careful examination of the complex postwar intellectual property litigation over 2,4-D and the correct distribution of scientific "credit" lies beyond the scope of this essay, one more claimant to independent (and prior) discovery must be mentioned. This is Franklin Jones of the American Chemical Paint Company, whose patent on the herbicidal use of 2,4-D and related halogenated aromatic compounds, and on the use of certain common emulsifying and spreading agents for applying the hormones, set off an immediate courtroom frenzy when it was granted in December 1945. "Jones, the American Chemical man," as he was known to the USDA scientists on whom he called, had served as a sales manager and traveling representative of the small Pennsylvania firm; his rivals might well have been suspicious that he caught wind of the 1944 results of Kraus and his BPI collaborators on one of his frequent visits to Beltsville.[21] For his part, Jones told an engagingly

[19] See J. F. Lontz, May 1941, "ESP-41-175," "Relation of Chemical Structure to Plant Hormone Activity," progress report of 15 Jan.–15 May 1941 (Plaintiff's Exhibit P-109); deposition of Wendell Tisdale, 13 Mar. 1947; and H. F. Dietz and Robert Sutton, 19 Mar. 1942, "Killing Experiments on Coleus, Greenhouse—Experimental Station" (Plaintiff's Exhibit P-116): Civil Action 5760.

[20] See Counsel for Plaintiff (i.e., Dow Chemical), "Petition for Declaratory Judgement," 28 May 1946, and "Petition to Amend," 6 May 1947, Civil Action 5760; and Counsel for Plaintiff (i.e., Sherwin-Williams), "Motion by Plaintiff for Summary Judgement," 26 Nov. 1946, Civil Action 850. For testimony see deposition of Wendell Tisdale, 13 Mar. 1947, pp. 64–65, 88–89, Civil Action 5760. The prior patents at issue are J. F. Lontz, U.S. Patent 2,322,761, issued 29 Feb. 1943, upon an application of 20 Feb. 1942; and A. E. Hitchcock and P. W. Zimmerman, U.S. Patent 2,341,868, issued 15 Feb. 1944, upon an application of 24 Sept. 1942. For the motives behind Boyce Thompson patents on hormones as understood by Du Pont see Patterson to Coolidge, 22 Oct. 1936 (Plaintiff's Exhibit P-119), Civil Action 5760.

[21] For the quotation see William Stewart to Kraus, 15 Feb. [1940], Botany Dept. Papers, Univ. Chicago, box 7, folder "Beltsville Correspondence." See also R. M. Salter memo, 28 Jan. 1946, "re Patent Application of Ezra J. Kraus"; and H. R. Foss to Kraus, 7 Feb 1946: Botany Dept. Papers, Univ. Chicago, box 7, no folder. The chief United States patent at issue was no. 2,390,941, issued 11 Dec. 1945 to Franklin D. Jones, on application of 4 May 1945. For the American Chemical version of discovery see Franklin Jones, 13 Aug. 1946, "Complainant's Deposition of Franklin De La Vergne Jones," p. 15, Civil Action 850.

simple story of how he had invented the new herbicides in February 1942: after happening to see some greenhouse tomatoes distorted by a commercial insecticide and sniffing what he guessed were chlorinated phenols, he made a few chlorinated phenols, tried them out on tomatoes and found some to be lethal, and tested these that summer on poison ivy in his yard. The entire invention process—from conception to reduction to practice—took no more than a few months and ten dollars, Jones claimed. There were very few documents produced to support the American Chemical chronology, however. The Jones patent application was first filed in March 1944; and while it is conceivable that this filing came about because Jones had heard of the early 2,4-D results of Kraus and Mitchell one month before, I would argue that it is more likely that Jones was inspired by Vernon Stoutmeyer. As already noted, Stoutmeyer discovered in 1942 that Zimmerman's 2,4-D had herbicidal properties, and in November 1942 he had ordered a new batch of the compound from a commercial supplier—American Chemical. Finding this to have an alarming odor and color absent from the sample he obtained from Zimmerman, Stoutmeyer evidently complained about its quality to his American Chemical contact—Jones—who replaced the order "on one of his trips" to the USDA in early 1943. Stoutmeyer testified that later in 1943 Jones told him that he was preparing an herbicide patent, evidence that fits the timing of the Jones patent application.[22]

Attorneys for American Chemical faced fierce challenges from the legal teams of Dow and Sherwin-Williams, who sued American when the firm threatened their dealers with infringement litigation, and also from USDA lawyers, who supported Kraus in an unusual effort to file a rival post-hoc patent claim. In the end Kraus dropped his own application, and the validity of the Jones patent versus that of the earlier Lontz patent was never decided by the courts. The thinking that led to American Chemical's decision to settle with its adversaries in late 1947 remains inaccessible to the historian, but it is reasonable to surmise that the firm's attorneys did not estimate their chances of victory very highly at that point. They had certainly known of the Lontz patent by 1944, when the patent office rejected Jones's initial application on the grounds that it duplicated Lontz, and they may have guessed that other major chemical firms would contest their claim on 2,4-D. But there is no evidence that American Chemical knew of Kraus's secret research or could have anticipated how it would bring the federal government into the case against the firm as well (for instance, an affidavit by Kraus submitted in testimony against American was supported by top-secret WBC documents especially declassified by the Army for the purpose—a move that provoked complaints by American Chemical's attorneys that access to such evidence was allowed only to their adversaries). Certainly the terms of the settlement accepted by American were not generous, considering the importance of the products at stake: to both Dow Chemical and Sherwin-Williams, both of whom had evidence that they had used herbicides during the war in collaboration with the Cornell group, American granted perpetual royalty-free licenses for a single $10,000 payment. American also granted a gratis royalty-free license to the government and agreed to license its patent to any manufacturer for fees not exceeding $10,000 annually. Cross-licensing arrangements with Du Pont for the Lontz patent were also established for all comers. Effectively, the

[22] See "Abandoned Application of Franklin D. Jones, serial number 527,358," filed 20 Mar. 1944; A. H. Winkelstein to Caesar and Rivise law firm, 20 June 1944; Caesar and Rivise, "Amendment to Application 527,358," 20 Dec. 1944, and attached letter to Patent Commissioner; and Winkelstein to Caesar and Rivise, 6 Mar. 1945: Civil Action 850. For Jones's version see Franklin Jones, 31 Jan. 1947, sealed "Affidavit of Franklin D. Jones, re Circumstances Surrounding Invention"; and "Affidavit of Franklin Jones, 29 Jan. 1947," p. 6: Civil Action 850. See also deposition of V. T. Stoutmeyer, 23 Apr. 1947, pp. 49–51, 64, Civil Action 5760.

government, some of the leaders of academic plant physiology (who, like Kraus, gave affidavits undermining Jones's claims), and the major players in the chemical industry had collaborated in blocking American Chemical's patent claims, making the new herbicide as widely, quickly, and cheaply available as market forces would allow immediately after the war.[23]

HORMONE HERBICIDES IN THE MARKETPLACE

As the legal struggles in the immediate aftermath of the war make plain, the chemical industry had quickly recognized that the hormone herbicides were potentially very valuable. Indeed, the actual commercial introduction of 2,4-D as an herbicide progressed extraordinarily quickly, ahead not only of the resolution of intellectual property issues but even of the lifting of official secrecy. Despite the cloak of censorship over herbicide reports in the biology literature, during 1945 the public became increasingly aware of herbicide developments, thanks more to industrial interests than to scientists. One of the first major stories on the subject in the national media appeared in the January 1945 edition of the farming magazine *Country Gentleman;* it announced the good news that innovative products of "physiological magic" (2,4-D and 2,4,5-T) "will be ready in 1945 to speed the fight which mankind has made down through the ages to protect crops from nature-strewn, unwanted plant forms which spring up, everywhere to choke and overrun." This ebullient piece focused on the published results of the Beltsville and Cornell groups and noted the potential agricultural utility, in particular, of 2,4-D's selective toxicity aginst broadleaf plants. While acknowledging that "giving accurate distributed credit" was difficult in this case, *Country Gentleman* awarded the most to "Dr. E. J. Kraus, of the University of Chicago, probably the most renowned physiological chemist in this country, if not in the world," and his collaborators. It is not clear whether the author noticed the footnotes crediting Kraus in the recent *Botanical Gazette* publications of his students or whether his information came directly from a Chicago-friendly scientist. The article also mentioned Franklin Jones, however, and noted that his firm was manufacturing and selling the new compounds under the brand name Weedone; this part of the story probably drew on American Chemical information sources. In February 1945 *Better Homes and Gardens* carried a piece focusing strictly on 2,4,5-T and its (nonselective) power to combat hated garden pests such as poison ivy and Japanese honeysuckle, that "Jap invader [which] has taken over large areas in the eastern United States" and which—in a continuation of the xenophobic, martial imagery typical of wartime—was said to overwhelm orchards like "a green wave . . . flow[ing] relentlessly over the landscape." *Better Homes* exclusively credited Jones as the inventor and noted that the miracle product was available as Weedone, sug-

[23] See "Stipulation Dismissing Suit," 23 Oct. 1947, Civil Action 850; and "Order Dismissing Suit," 10 Dec. 1947, *American Chemical Paint Co. v. Dow Chemical Co.,* Civil Action 36–322, Southern New York District Federal Court, held at National Archives and Records Administration Records Storage Facility, New York City. On Kraus's own patent scheme see Salter memo, "re Patent Application of Ezra J. Kraus" (cit. n. 21); J. P. Cullinan to Kraus, 5 Feb. 1946; Foss to Kraus, 7 Feb. 1946; A. J. Kramer to Kraus, 25 June 1946, and attached patent application no. 1949: Botany Dept. Papers, Univ. Chicago, box 7, no folder. On Kraus's affidavit and the evidence behind it see Fred to Kraus, 11 Jan. 1943; Col. J. H. Rothschild to Kraus, 20 Jan. 1947; and "Affidavit of E. J. Kraus," 22 Jan. 1947: Civil Action 850. On insinuations of conspiracy against American Chemical see comments of Charles Rivise, in "Transcript of Hearing, Civil Action 850," 7 Feb. 1947, pp. 85–86, Civil Action 850; similarly, see deposition of V. T. Stoutmeyer, 23 April 1947, pp. 95–96, Civil Action 5760. Interestingly, Thimann of Harvard broke with Kraus by submitting an affidavit supporting the novelty of Jones's patent: "Affidavit of Kenneth V. Thimann," 24 Jan. 1947, Civil Action 850.

gesting that American Chemical was the main information source. The July 1945 *Reader's Digest* condensation of this story, "Death to Weeds!" reached an even wider audience with its warlike message and generated, Jones would later testify, more inquiries than any story in the magazine's history to that point.[24] By the actual end of the war in August 1945 there was little the public did not know about the new chemicals—except that they might have military as well as horticultural and agricultural applications.

With the end of the war, Kraus pushed the government to end the censorship and publicize his work and that from Camp Detrick for the sake of agriculture. By the time the censorship was lifted, around the beginning of October 1945, Weedone had been on the market for a year and was being heavily advertised by American Chemical. American, which doubled its market presence by buying out the pesticide business of the rival Koppers firm (and with it the well-known herbicide brand Weedex) in late 1945, was not the only chemical company driving hard to exploit the new products. Sherwin-Williams built manufacturing facilities and was moving vigorously into the civilian market by the end of 1945, followed closely by fellow giant Dow. While chemical firms began whipping up a storm of publicity for 2,4-D, some (such as Dow) so rapidly courted away the Camp Detrick scientific staff in their eagerness for research talent to discover the next miracle hormone that the survival of the military group was jeopardized.[25] Other firms hired senior plant physiologists who could build growth regulator discovery programs, among them van Overbeek, who left Caltech to became a research manager at Shell. The market segment initially targeted was the suburban consumer looking to control broadleaf weeds in grassy lawns—which, as Mitchell's USDA group had already shown, required little more than wetting a lawn in summer with a certain concentration of 2,4-D. Thus in 1945–1946 the Sherwin-Williams advertising campaign for its Weed-Be-Gone 2,4-D product featured such images as a fashionably dressed woman daintily killing weeds with a watering can juxtaposed with a stooped, sweating man ripping vainly at dandelions, or a white suburban home with a lawn "strangled to death by thousands of soil-grasping leafy weeds" before treatment but "lustrous" afterward, at a cost of only a dollar. "Every lawn lover on every street in your community is a Prospect for Weed-No-More," Sherwin-Williams dealers were exhorted, so "'cash in' on the Biggest National Advertising Campaign in weed history!" This campaign alone generated some 175 million advertising messages in 1946. (See Figure 4.) Convenience and ease were also central to American Chemical's campaign, which featured the theme "Kill Lawn Weeds with Weedone" and images of suburban homes with sweeping, spotless lawns. The new ease and affordability of a perfect lawn was the motif most often underscored in a host of enthusiastic newspaper and magazine stories on the products as well; such media coverage naturally amplified the impact of the

[24] J. Sidney Cates, "A Knockout for Weeds," *Country Gentleman,* Jan. 1945, pp. 12, 33 (quotation on p. 12); R. Milton Carleton, "New TCP Kills Toughest Weeds," *Better Homes and Gardens,* Feb. 1945, pp. 15, 93–95 (quotation on p. 95); Carleton, "Death to Weeds!" *Readers Digest,* July 1945, pp. 76–77; and Franklin Jones, 13 Aug. 1946, "Complainant's Deposition of Franklin De La Vergne Jones," pp. 85–86, Civil Action 850. For attitudes toward Japanese cherry trees that are quite similar to those toward Japanese honeysuckle see Philip Pauly, "The Beauty and the Menace of the Japanese Cherry Trees: Conflicting Visions of American Ecological Independence," *Isis,* 1996, *87*:51–73.

[25] Rivise, 7 Feb. 1947, "Transcript of Hearing, Civil Action 850," p. 75; and Jones, 14 Aug. 1946, "Complainant's Deposition of Franklin De La Vergne Jones," p. 144: Civil Action 850. For Kraus's efforts to lift censorship rules see Kraus to Zimmerman, 12 Mar. 1945, Botany Dept. Papers, Univ. Chicago, box 7, folder "Censorship"; Kraus to Tukey, 23 May 1945, Botany Dept. Papers, Univ. Chicago, box 7, no folder; and Kraus to Col. H. N. Worthley, 22 Oct. 1945, Botany Dept. Papers, Univ. Chicago, box 7, folder 1. On the impact of industrial recruitment at Camp Detrick see A. G. Norman to Kraus, 18 Oct. 1945, Botany Dept. Papers, Univ. Chicago, box 7, folder 1.

Figure 4. *Advertisement for a 2,4-D lawn-care product, from the* Saturday Evening Post, *1946. Copyright Sherwin-Williams Company; used with permission.*

advertising clamor around 2,4-D products. These chemicals democratized the expansive, grassy yard that has helped define the American suburban ideal since the late nineteenth century by removing the need for a gardener. Thus herbicides played a crucial, underappreciated role in facilitating America's postwar sprawl into leafy green suburbia, even if their ecological and economic impact was ultimately far greater as an agricultural technology.[26]

[26] See Weed-Be-Gone advertisements in *Better Homes and Gardens,* Mar. 1946, p. 131; and *San Francisco Shopping News,* 22 Apr. 1946, p. 16. Weedone full-page advertisements are in *Better Homes and Gardens,* Mar. 1946 (no pagination); and *Horticulture,* 14 Apr. 1946, *24,* back cover. For newspaper accounts see, e.g., "Weed Killer Developed at Ohio Station," *Waynesboro News-Virginian,* 26 Feb. 1946, sec. 1, p. 5; and William White,

Sales to farmers for use in field crops—though already envisioned by Kraus and presumably by chemical firms as well—would require careful trials by experiment stations to develop treatment regimes that would balance yields and costs for each crop. The agricultural research community was eager to try out the new chemicals and develop these detailed usage protocols and so needed little urging in 1945 and 1946 to begin field trials. Perhaps the experiment station weed scientists wished to keep up with their entomologist colleagues, who had been, in the words of the historian John Perkins, thoroughly "chemicalized" (converted to chemical pest control exclusively, not just as one method among many, and inspired to emulate the perceived scientific rigor of chemists) by the wartime introduction of DDT.[27] Fanning the flames, Kraus did his share of publicizing among the agricultural scientists; in fact, he ate one-half gram of pure 2,4-D per day for three weeks to demonstrate its safety. But already by late November 1945, when Kraus gave the keynote speech at the Second Annual North Central States Weed Control Conference in St. Paul, Minnesota, there was so much excitement about 2,4-D as the solution to every farming problem that Kraus was confident enough to shift the attention of the agricultural scientists and state officials gathered there onto what he considered the big picture:

> [My] feeling is that there is not a single thing that deals with living plants that is not eventually going to find its solution through the application of growth-regulating substances. It may not be 2,4-D. It may not be a whole strings of "Ds." . . .
>
> We are going to make plants grow taller, if you wish them taller, and shorter, if you want them shorter. We are going to have them grow thicker, if you want them thicker, and thinner, if you want them thinner. . . .
>
> I should like to say, what we need is more investigations, and fundamental research, but I have heard that phrase so much that I would like to touch it off with an atomic bomb.

In conclusion, he reiterated: "I know of no single process of the living plants that cannot be brought eventually under absolute control" through further research on growth regulators. Thus the original dream of engineering plant life through synthetic hormones was still very much alive for some plant physiologists, even after the discovery that these compounds were particularly effective for destroying plants. Sherwin-Williams, for one, gave a vote of confidence to Kraus's vision by awarding him a five-year research contract, at $25,000 per year, in December 1945. Offering both basic biological insights and industrial utility in the foreseeable future, plant physiology was now becoming an applied science, and physiologists requiring more funding for their hormone research did not need to await the resolution of the national debates on the form that postwar federal support for science should take.[28]

"Science Decrees Death for Lawn Weeds," *Pittsburgh Press,* 1 June 1946, sec. 3, p. 1. On the Sherwin-Williams advertising campaign see P. B Willis memo to sales distribution list, 14 Apr. 1946; and ACME White Lead & Color Works to "Our Dealers," 26 Dec. 1945 (quotation): Defendant's Exhibits 3 and 4, Civil Action 850. On the rise of the suburban lawn see Kenneth Jackson, *Crabgrass Frontier: The Suburbanization of the United States* (New York: Oxford Univ. Press, 1985), esp. pp. 58–61; and Virginia Jenkins, *The Lawn: History of an American Obsession* (Washington, D.C.: Smithsonian Institution Press, 1994). On its ecological implications see F. Herbert Bormann, Diana Balmori, and Gordon Geballe, *Redesigning the American Lawn: A Search for Environmental Harmony* (New Haven, Conn.: Yale Univ. Press, 1993).

[27] Perkins, "Reshaping Technology in Wartime" (cit. n. 1); Perkins, *Insects, Experts* (cit. n. 2), p. 22 (quotation); Palladino, *Entomology, Ecology, and Agriculture* (cit. n. 2); and Dunlap, *DDT* (cit. n. 4).

[28] Ezra J. Kraus, keynote address, *Proceedings of the North Central States Annual Weed Control Conference,* 1945, *2:*75–81. On Kraus's contract with Sherwin-Williams see minutes of 13 Dec. 1945, Meetings of Trustees of the University of Chicago 1945–1946, University of Chicago Archives. For a recent perspective on economic forces behind the debates about science funding in postwar America see Daniel Kleinman, "Layers of Interest, Layers of Influence: Business and the Genesis of the National Science Foundation," *Sci. Technol. Hum. Val.,* 1994, *19:*259–282.

CONCLUSION

Though Kraus's own research on synthetic hormones would lead to no other new technology, work by the agricultural station scientists quickly made the new product category of hormonal herbicides popular with farmers and profitable for the chemical industry. They showed how, by spraying 2,4-D and similar chemicals, farmers could control a wide range of weeds not only in monocotyledonous crops such as maize and small grains but even in many broadleaf crops, from strawberries to potatoes. By 1949 U.S. production of 2,4-D had reportedly reached 20 million pounds, and that year some 25 million acres were sprayed in the Great Plains region alone, where it was already becoming standard practice for spring wheat production. Herbicides have become an even more important part of the modern farming system than insecticides, at least as measured by quantity used and market size: by the mid 1990s, over $4 billion was being spent on herbicides in the United States each year, three times more than on insecticides. Far from rendering the products obsolete, a large proportion of today's agricultural biotechnology research is directed at extending and enhancing the use of herbicide-based weed-control practices. Thus we still live under the sway of the technological momentum established by herbicides in the immediate postwar years.[29]

What role did World War II play in establishing this momentum? The war helped trigger the rupture of a conceptual barrier that hindered plant biologists of the 1930s: the notion that plant hormones were (only) growth stimulators. In the case of Kraus's group, it seems that the war mobilized the interest of these plant physiologists in finding new, militarily relevant applications for their existing objects of study, the hormones. A similar claim might be made for the British plant physiologists, though archival research on them remains to be done. It seems likely, however, that even without the explicitly military project of Kraus's group or the government-coordinated English project, both set in motion by the war, the herbicidal use of 2,4-D and other powerful synthetic plant hormones would have been recognized before long, perhaps belatedly by Du Pont, perhaps by another chemical firm (though probably not by American Chemical, which seems to have been inspired by Jones's contact with the work of Stoutmeyer and, possibly, Kraus's group). As for the Chicago and USDA plant physiologists, it does not appear that new access to resources for research made possible by their military contracts, the greater scale of the work undertaken, or increased interactions with scientists in other fields played a decisive role of the sort that the wartime insect-control project had in the entomologists' conversion to DDT (or, for that matter, the major role such factors played in the conversion of some high-energy physicists to weapons research). Rather, plant physiologists assigned to military herbicide research brought the weed-killing potential of hormones to the attention of

[29] E.g., R. F. Carlson, "Control of Weeds in Strawberry Plantings by the Use of 2,4 Dichlorophenoxyacetic Acid," *Proceedings of the American Society for Horticulture Science,* 1947, *49*:221–223; C. J. Willard. "Plant Regulators for Weed Control," in *Plant Regulators in Agriculture,* ed. H. B. Tukey (New York: Wiley, 1954), pp. 184–201; R. J. Aldrich and C. J. Willard, "The Effect of Post-Emergence 2,4-D on Corn," *Proceedings of the North Central States Annual Weed Control Conference,* 1949, *6*:55–56; and L. M. Stahler, "The National Picture in Aerial Spraying for Weed Control in 1949," *ibid.*, pp. 37–41 (the acreage figures for the Plains region included Canada, while the production figures did not). On economics and ecology related to current herbicide use see Krimsky and Wrubel, *Agricultural Biotechnology and the Environment* (cit. n. 4), Ch. 2. On "momentum" and other issues related to technological determinism see Thomas Hughes, "Technological Momentum," in *Does Technology Drive History? The Dilemma of Technological Determinism,* ed. Merritt Roe Smith and Leo Marx (Cambridge, Mass.: MIT Press, 1994), pp. 101–113; see also the other contributions in the same volume.

agricultural scientists and the chemical industry, and this was enough to spark an interest in developing detailed methods for application. The role of World War II in precipitating the breakthrough may simply have been its general stimulation of applied work among basic plant scientists. In addition, the war set the stage for apparently simultaneous discoveries—and for disputes over priority—by suppressing normal publication for several years. Certainly the conceptual shift that allowed the recognition of hormones as useful herbicides was facilitated by some type of "external" change in the practical aims or the social context of plant biology brought about by the war. That is, there is no evidence at all that major "internal" theoretical changes either drove this conceptual shift or followed directly from it, as occurs with archetypal Bachelardian or Kuhnian discontinuous "revolutions" in science.[30]

Once the conceptual block was lifted and the comparatively simple experiments to assess the toxicity of synthetic plant hormones were done, the adaptation and uptake of the technology for farm use occurred so quickly as to resemble the crystallization of a compound from a supersaturated solution. Wartime had contributed to the socioeconomic context in which American industry was ready to convert these novelties of science to mass commodities with astonishing speed, as soon as—or even before—peace returned. Though volumes could be written on the broader cultural and economic reasons for the rapid success of 2,4-D in postwar agriculture, it is worth touching on a few of the many responsible factors. Culturally, we can easily detect (for example, in enthusiasm for 2,4-D and DDT use in the home) the widespread appeal that technological control over and subjugation of nature has exerted throughout the modern era, a confidence in science and technology perhaps at its highest point ever in the immediate aftermath of World War II. Economically, two different classes of forces must be distinguished, one affecting supply by industry and the other demand from the farmer. On the supply side, hormonal herbicides were very important new products for the American chemical industry, taking their place beside new insecticides like DDT and cheaper nitrogen fertilizers in its conversion to a peacetime footing through redirection to agricultural markets. With their renewed push into such established lines of agricultural products as insecticides and fertilizers, chemical firms that sold the new herbicides as well achieved synergies by using the same distribution networks. The bulk price of pure 2,4-D, which was easily synthesized with existing technology and from cheap materials, phenol and chlorine, had already dropped to \$0.53 per pound by mid 1946. On the demand side, selective herbicides are economical substitutes for labor-intensive methods of weed control. Thus the large farm labor shortage that began in the war period and continued into the manufacturing boom years afterward is pertinent, as farmers who chose to use herbicides would be less dependent on expensive and scarce labor for weed control. Perhaps there was a pent-up demand for such products on farms, a weed problem that had built up unchecked during the war. And this method of weed control must have seemed especially economical to farmers converting to insect control based on DDT, since they could use much of the same spraying equipment to apply herbicides. Moreover, federal farm subsidies and price supports, begun in the New Deal era and continued through wartime and into the peace, would have made the borrowing necessary to purchase such equipment a safer financial decision for many farmers. Thus

[30] Perkins, "Reshaping Technology in Wartime" (cit. n. 1); Forman, "Behind Quantum Electronics" (cit. n. 1); Thomas Kuhn, *The Structure of Scientific Revolutions*, 2nd ed. (Chicago: Univ. Chicago Press, 1970); and Tiles, *Bachelard, Science, and Objectivity* (cit. n. 3).

one can invoke both demand-side "pull" and supply-side "push" in explaining the quick acceptance of the new agricultural herbicides.[31]

Even if the war stimulated both demand and supply, releasing latent forces that made postwar realization of the agricultural potential of hormonal herbicides virtually certain, it certainly did not create the socioeconomic situation in which Zimmerman's synthetic hormones could leap so easily from Camp Detrick to the farm. As I noted in the introduction, capital-intensive agriculture had been in the ascendant since the late nineteenth century. But neither did overarching free-market economic forces establish this enduring context that so strongly favored the uptake of chemical weed-control technology. Even leaving aside the role of subsidies and price supports, which generally were not (or, at any rate, not always) intended to promote capital-intensive farming, deliberate government intervention played a key role in this trend in the United States, particularly in the interwar period. For example, the commercialization of grain seed production depended on systematic efforts by government agricultural agencies: the basic breeding work from which arose the hybrid maize that first made seed corn economically viable as a commodity was done at public expense by USDA and state agricultural geneticists, who were then made to leave the corn improvement field once private enterprise took it over in the 1930s. Indeed, the majority of USDA farm "modernization" initiatives since World War I have been described as selectively beneficial to capital-intensive, large-scale, industrial agricultural production.[32] Another good example has been discussed in this essay: even before the war, Kraus was engaged by the USDA to build federal research programs aimed at applying hormones to agriculture.

This government-assisted impetus to "modernize" agriculture through the use of synthetic hormones, which began before the war, continued right through it, nothwithstanding the shift to more specifically military goals for Kraus and some of the other protagonists. The role of other discoverers aside, Kraus and the USDA scientists under military contract contributed significantly to revealing the utility of hormones as agricultural herbicides, accelerating this technological innovation and its postwar spread. Stoutmeyer's volunteer efforts—pursued, like Kraus's, on his own initiative apart from his official duties during the war—similarly show that this impetus was not just a matter of policy but was internalized in the USDA research culture. After the disovery of the new herbicides, the federal

[31] On the general history of the chemical industry and some of its leading firms in the mid-twentieth century see Hounshell and Smith, *Science and Corporate Strategy* (cit. n. 17); Carol Kennedy, *ICI: The Company That Changed Our Lives,* 2nd ed. (London: Chapman, 1993); Raymond Stokes, *Divide and Prosper: The Heirs of I.G. Farben under Allied Authority, 1945–1951* (Berkeley: Univ. California Press, 1988); and the contributions in Mauskopf, ed., *Chemical Sciences in the Modern World* (cit. n. 9). On the 1946 price of 2,4-D see Jones, 13 Aug. 1946, "Complainant's Deposition of Franklin De La Vergne Jones," pp. 177–178, Civil Action 850. On the adoption of DDT by farmers see Perkins, *Insects, Experts* (cit. n. 2); and Dunlap, *DDT* (cit. n. 4). On the fertilizer industry see Nelson, *History of the U.S. Fertilizer Industry* (cit. n. 2). On federal farm subsidies and price supports see John Opie, *The Law of the Land: Two Hundred Years of American Farm Policy* (Lincoln: Univ. Nebraska Press, 1987); Albert Hart, Margaret Reid, Theodore Schultz, and Walter Wilcox, eds., *Wartime Farm and Food Policy, Pamphlets 1–11 (1943–45)* (New York: Arno, 1976); Willard Cochrane and Mary E. Ryan, *American Farm Policy, 1948–1973* (Minneapolis: Univ. Minnesota Press, 1976); Graham Wilson, *Special Interests and Policymaking: Agricultural Policies and Politics in Britain and the United States of America, 1956–70* (New York: Wiley, 1977); and Milton Hallberg, *Policy for American Agriculture: Choices and Consequences* (Ames: Iowa State Univ. Press, 1992).

[32] Palladino, *Entomology,* (cit. n. 2); Kloppenberg, *First the Seed* (cit. n. 4); Fitzgerald, *Business of Breeding* (cit. n. 3); Nelson, *Ecology, and Agriculture History of the U.S. Fertilizer Industry;* Hightower, *Hard Tomatoes* (cit. n. 4); Grant McConnell, *The Decline of Agrarian Democracy* (Berkeley: Univ. California Press, 1953); and Michael Fox, *Agricide* (New York: Schocken, 1986). On tensions around the issue of farm "modernization" see also David Danbom, *The Resisted Revolution: Urban America and the Industrialization of Agriculture, 1900–1930* (Ames: Iowa State Univ. Press, 1979).

government (both the USDA and the Army) seems to have played a significant role behind the scenes in making them as cheap as possible by supporting the challengers of American Chemical's patent. And, of course, with the end of the war agricultural extension scientists devoted considerable effort to developing weed-control regimes so that farmers could effectively use the new herbicides being marketed by chemical companies. Thus the case of 2,4-D and similar herbicides is another in which the state has assisted private industry in developing technologies that make farming ever more capital intensive. The war seems even to have occasioned an amplification of government influences on agriculture in the United States, quite apart from the indirect economic influences already noted. This is clearly true for chemical insecticides: wartime research agencies both funded the development of usage regimes for DDT by entomologists (many of them from the USDA) and financed the construction of large DDT factories through military orders for the material. Similarly, the American chemical industry's postwar business in synthetic fertilizers was massively, if somewhat more indirectly, state subsidized in that the federal government roughly doubled the nation's nitrate production capacity during World War II by building explosives factories (and in some cases also the hydroelectric schemes that powered them) and then immediately after the war sold them off to industry at bargain prices.[33]

This pattern of government intervention in agriculture through peace and war opens to question the inevitability of the changes that have happened on the farm during the twentieth century—the trends toward ever-greater concentration and capital intensity—together with the social and ecological impacts of industrial farming. History shows that these trends have owed a great deal to state influence (sometimes magnified and justified by war efforts); unless we adopt the unseasonable premise that government is nothing more than another instrument of capital itself, it stands to reason that feasible alternatives might also be realized through appropriate government-funded research and public policy supporting it.

[33] Perkins, "Reshaping Technology in Wartime" (cit. n. 1); and Nelson, *History of the U.S. Fertilizer Industry.*